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EVALUATION OF SEISMICITY AT U.S. RESERVOIRS

by

W. Daly, W. Judd, R. Meade

USCOLD

Committee on Earthquakes

May 1977

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COMMITTEE ON EARTHQUAKES

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Printed at California Institute of Technology
May 1977

Foreword

This report presents data relevant to the occurrence of reservoir-associated earthquakes. The possible occurrence of earthquakes, presumably associated with reservoir loading, that cause intense shaking at a dam-site strong enough to damage the dam, as in the case of Koyna, India and Hsinfengkiang, Peoples Republic of China, poses a problem to the designers of dams. The Committee on Earthquakes is studying the problem and this report is the first that addresses the subject of the occurrence of earthquakes near dams. The Committee has issued an earlier report "Seismic Instrumentation of Dams" by Bruce A. Bolt and Donald E. Hudson, April, 1975, which also appeared in the Journal of the Geotechnical Division, American Society of Civil Engineers, GT11, November 1975.

The Committee on Earthquakes collects, analyses and publishes data relevant to earthquake hazards and the design of dams, and identifies areas where additional research is needed. The project for preparing this report received partial support from the National Science Foundation. Any findings, opinions, conclusions or recommendations presented in this report are those of the authors and not of the National Science Foundation.

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INTRODUCTION

The phenomenon of reservoir-associated seismicity has aroused considerable interest in the international scientific and engineering communities. However, this phenomenon appears to have been of concern in the United States as early as the 1870's, when the U. S. Army Corps of Engineers rejected a proposal for an impoundment in the Salton Basin (10) on the basis that the reservoir might generate earthquakes. In recent years there has been an increase in reports that seismic activity can accompany the construction and impoundment of successively larger dams and reservoirs. Bozovic and Rothe, among others, have prepared lists of reservoirs experiencing such phenomenon worldwide (5, 22, 23). In several instances, notably at Koyna in India and Kremasta in Greece, earthquakes, reportedly associated with their reservoirs, caused significant loss of life and structural damage. To date there is only circumstantial evidence for some earthquakes being caused by reservoir loading, the data necessary for scientific proof have not been obtained.

Within the United States, the best-documented case of such activity is Lake Mead, with over 30 years of records. Also, Mickey (18) examined a sample of United States dams and found what appeared to be a cause and effect relationship at only ten sites. However, of these, only the Lake Mead records appeared to present a statistically meaningful relationship between reservoir fluctuations and seismic activity. Because of the claims and counterclaims regarding the influence of reservoirs, the Committee on Earthquakes of the United States Committee on Large Dams inaugurated this study to evaluate the degree of seismicity at reservoirs in this country. It was believed that an evaluation of the data would indicate to what extent such impoundments enhanced, in a statistical sense, the reported local seismicity.

This paper summarizes the current state of knowledge regarding reservoir-associated seismicity and evaluates the results of the survey of seismicity at large dams in the United States.

DIFFERENTIATING CHARACTERISTICS

Reservoir-associated seismicity may differ in several respects from regional seismicity in locations where both types have been experienced. The primary differences are found in the parameters of the Gutenberg-Richter relationship* and in the foreshock-aftershock pattern.

Generally, the b-values* in the Gutenberg-Richter equation are greater for the aftershocks in a given sequence than for the foreshocks. In studies of 4 earthquakes of magnitude 4 to magnitude 8 in Japan, Greece, Alaska and Chile, foreshock b-values ranged from 0.3 to 0.6, approximately one-half the values for the aftershocks. However, for the events at the Kariba, Koyna and Kremasta reservoirs, the foreshock b-values were comparable to or greater than the aftershock values. Additionally, both values were higher than the regional b-values and the b-values observed for the aftershock sequences of other earthquakes. These b-values were

*b-values refer to the value assigned to the slope in the Gutenberg-Richter frequency-magnitude relationship $\log N = a - bM$, where N is the cumulative frequency of all earthquakes of magnitude M or larger.

tested for statistical significance using the F-test*; the results indicate that the differences are significant at a 95% confidence level (12, 13, 15).

Prior research had suggested that if a high b-value (greater than 0.5 to 0.6) is exhibited in a foreshock sequence, a large earthquake of magnitude 8 may be expected (2). But at Kariba, Koyna and Kremasta, the main shocks had magnitudes of about 6 although the b-values were all greater than 1. A study of California earthquakes indicated that for sequences with low b-values in the foreshock sequence the largest aftershock is at least 90% of the magnitude of the main shock. This value generally decreases to 60% to 70% for higher b-values. At Koyna, both the b-values and the aftershock/main shock ratios were high (15).

In summary, the relationship between foreshock and aftershock b-values, the relationship between b-value and the earthquake magnitude and the ratio between the maximum aftershock magnitude and the main shock magnitude appear to be substantially different for reservoir-associated seismicity than for natural regional seismicity (12, 13, 15). Tables 1 and 2 present results of several analyses of the Gutenberg-Richter parameters in relation to reservoir-associated seismicity.

Mogi studies foreshock and aftershock patterns experimentally in the laboratory and has compared his results with natural earthquakes (19). He classified foreshock-aftershock patterns derived from his experiment into three types: In the Type I model, no foreshocks occur; in the Type II model there are foreshocks which abruptly increase in frequency at the

*The F statistic is commonly used in analysis of variance. However, it is also valid to compare a ratio of "b" values. A rigorous development is given by Utsu. (Journal of Physics of the Earth, Vol. 14, No. 2, 1966, pp. 37-40).

time of the main shock; and the Type III model represents a swarm activity. The foreshock-aftershock patterns at Kariba, Koyna and Kremasta are similar to the Type II model. This model corresponds to a heterogeneous, prefractured structure subjected to asymmetric exterior forces. The normal earthquakes of these regions correspond to the Type I model. This difference in foreshock-aftershock patterns indicates that if reservoir-associated seismicity occurs it will be a unique phenomenon that apparently is unrelated to normal regional seismicity (14, 15, 23).

COMMON FEATURES

Several generalizations about reservoir-associated seismicity have been proposed by different investigators (5, 13, 14, 17, 20, 22, 23). Among these are the following:

1. Seismicity apparently results from impoundment rather than from dam construction because no significant shocks have been observed after construction and before reservoir filling.
2. Seismicity increases considerably after water impounding, with epicenters confined to the reservoir vicinity.
3. Seismicity increases and decreases with fluctuations of the water level and the most severe earthquakes follow the highest rate of loading.
4. As the water level drops, energy release diminishes although the shocks do not cease.

5. Seismicity apparently is not directly related to the volume stored as many reservoirs with large impounded volumes do not exhibit seismicity. Activity tends to be most evident when water depth is greater than 100 meters. Depth of water therefore appears to be more important than the volume impounded.
6. Although seismic activity may be initiated almost as soon as impoundment begins, the time of maximum activity occasionally shows a definite time lag following attainment of maximum reservoir level. Seismicity is related to rate of filling of reservoir with rapid filling more apt to induce earthquakes.
7. Reservoir-induced events are characterized by relatively shallow foci and modest magnitudes in most cases.
8. In many cases the strongest shocks follow numerous foreshocks with the frequency and magnitude of the foreshocks increasing progressively.
9. Special geologic conditions are apparently necessary for reservoir-associated seismicity. While conditions may be different at various sites, they generally include certain tectonic situations which can give rise to seismic phenomena.
10. The maximum values of magnitude and intensity due to impounding are not increased above the natural seismicity levels.
11. Little or no induced seismicity will occur at those reservoirs in the proximity of thrust or low-angle faults. (This factor was reported at the 1st Intern. Symp. on Induced Seismicity in Banff, Canada, Sept. 15-19, 1975; part of the proceedings are to be published in 1977 issues of Engineering Geology).

WATER LEVEL VS. SHOCK FREQUENCY

Several investigators have examined the possible correlation between water level and shock frequency (11, 12, 13, 15, 16, 21, 22, 23). They indicate that the factors that may affect tremor frequency near reservoirs include:

1. Rate of water level increase
2. Duration of filling
3. Maximum water level achieved
4. Duration water level is maintained

In 1974, H. K. Gupta and his colleagues (13) established that the correlation coefficients between water level and tremor frequency at Koyna, Kariba and Kremasta were +0.93, +0.74 and +0.69, respectively.

In support of this assertion of a high correlation between water level and tremor frequency, a number of examples of this apparent relationship have been cited. Several of these cases will be summarized below.

Earthquakes were felt in the area of Hoover Dam for the first time in September, 1936 when lake level reached the maximum for the year. Maximum seismic activity and the strongest earthquake (magnitude 5) occurred in May, 1939 when the lake again rose above the normal level. The other two significant rises in lake level (1941 and 1942) were both followed by significant seismic activity within a few weeks of achieving maximum levels.

The three major rises in the level of the Vaiont Reservoir in Italy were followed by bursts of seismic activity. Also, the decrease in water level following every peak was followed by decreased seismic activity. The earthquake in May, 1960 and the series of earthquakes in October-December, 1960 can be correlated with the rise in reservoir level throughout the year. The highest reservoir level recorded was achieved in September, 1963 and conspicuous seismic activity was observed from May through September of that year. The maximum activity of September, 1963 was followed by the disastrous landslide of October 9, 1963. (We do not necessarily imply a cause-and-effect relationship here as this catastrophe has received extensive studies that are not all in agreement as to the cause of the landslide.).

The outbreak of seismic activity at Kariba Dam in 1959 corresponds to the start of filling at a high rate. Maximum activity and the greatest shocks occurred in 1963 when the lake level was at its maximum.

At Kremasta Dam, a high rate of water level increases was followed immediately by an increase of seismic activity. The peak activity occurred in February, 1965, immediately after a long period of loading at a high rate. During March, 1966 and afterwards the activity decreased when the reservoir level remained approximately constant.

Seismic activity at Koyna Dam is apparently influenced by the water level in the reservoir, the loading rate of the reservoir and the duration for which the water level is maintained. Seismicity is found to increase every year following the rainy season. The highest water level was maintained for the longest duration during August-December, 1967 which was also the period of maximum seismic activity. The lesser rate of loading and the consequently lower levels following the rainy seasons of 1964 and 1966 were followed by lesser seismic activity and larger time lags.

CURRENT THEORIES

A basic assumption in most if not all current theories is that the earthquake results from a stress failure in the rock system at depth. The more frequently cited theories as to the causes of reservoir-associated earthquakes are the following (3, 6, 7, 8, 15, 17, 20, 23):

1. Existing tectonic stresses may be such that the crust is in a state of precarious equilibrium. In such a situation, the reservoir weight may cause only a slight increase in such stresses, but this increase may be just enough to trigger earthquakes.
2. Water can act as a lubricant and decrease the frictional resistance of rock fracture surfaces sufficiently to cause movements that will initiate earthquakes.
3. Increase in the pore pressure in fracture zones reduces the effective stresses and the resultant decrease in shear resistance initiates seismic activity. Laboratory studies by Brace (21) support this possibility and indicate the earthquakes would be caused by strike-slip or dip-slip motion.

Gupta, et al (13, 15) have suggested that the reservoir changes the mechanical properties of the rock system by making it more heterogeneous. This may effectively divide it into smaller volumes which will release their stored energy individually as their strength is exceeded. Seismicity then would be characterized by the occurrence of a number of smaller earthquakes and a high foreshock activity before the major event. This would explain the similarity of a reservoir-associated seismicity to Mogi's Type II Model, the high b-value and the large aftershock/main shock ratio.

All investigators have emphasized the importance of regional geology and the state of stress in the earth. Geologic factors to be considered include rock type; nature of bedding planes, joints and faults; and physical, mechanical and chemical properties of the rock mass.

STATE OF STRESS

Nikolaev (20) has made several generalizations relating stress conditions to tectonics:

1. For areas of completed folding, crystalline covers and regions which have been subjected to intensive tectonic movements, rock system stresses exceed geostatic pressure and vary as to the magnitude and orientation of their components.
2. "in areas of weak mobility...the field of stresses is more homogeneous."
3. In most regions the maximum principal stress is horizontal and appears to be similar to the stress generated in earthquakes in the more seismically active areas of the Earth.

Lane (17) summarized two conflicting theories for the state of stress in the earth's crust:

1. One hypothesizes that the stress field is three-dimensional with all three stresses generally compressive; the two horizontal components are generally of greater magnitude than the vertical stress, and their magnitudes and directions are strongly controlled by the direction of joints and faulting (the explanation for the large horizontal stresses is that the earth is shrinking).

2. The other is the plate tectonics theory which can be interpreted as evidence that the earth is expanding; this theory also is consistent with the existence of large horizontal compressive stresses in the crust. In view of this stress condition, it is probable that the added weight resulting from the reservoir would increase the stability of the rock system because it would decrease the shear stresses. The weight of the dam and its reservoir seems unlikely to cause a rock-system condition whose failure results in earthquakes.

REGIONAL GEOLOGY

Since the great majority of large reservoirs do not appear to have induced seismic events local conditions, especially geology and state of stress, must be the decisive factors in determining if a reservoir is likely to cause an earthquake at a given site. Castle et al (8), in examining the influence of regional geology, refers to the tectonic state of a site, i.e., existing fractures, accumulated elastic strain, and deformational mode. Study of these factors at most sites which have experienced apparent reservoir-induced seismicity reveal that the tectonic state of these sites is typified by the presence of steeply dipping faults, high elastic strain rate, and either extensional or horizontal shear strain, but no one of these three factors is sufficient to indicate that the site is prone to reservoir-induced seismicity. Deformation mode is the most significant factor and the existence of nearby fractures appears to be the least significant. Thus classification of tectonic state provides a framework to evaluate the probability of whether a particular site may be prone to reservoir-induced seismicity.

PORE PRESSURE EFFECTS

The effects of pore water interacting with a particular geological structure and stress field are of primary importance in reservoir-associated seismicity. For example, raising of the ground water table by the reservoir will cause an increase in pore pressure. If the ground is uniform, the changes of stress in all three directions will be similar and there will be a tendency to increase the stability. A different situation exists, however, when we consider a fault zone extending to a great depth or distance from the reservoir and which is accessible to reservoir water. In this case the effect of impounding is to increase the water pressure in the fractured zone. Dependent upon the permeability of the fault zone, there also may be a time effect in the transmission of these fluid pressures. Water is compressible and a column of water several kilometers in length must be considered. As a result elastic compression of the water may be several centimeters and the transfer time may be of the order of several days to many months per kilometer. Comparatively, the time for transfer of the pressure within the adjoining rock system will be longer. Thus there will be an interval when the pore pressure in the faulted zone is greater than the pore pressure in the adjacent rock.

If the material also is subjected to a high shear stress, the reduction in normal stress caused by pore water pressure can result in failure and movement of the faulted zone. The conditions for such a failure are as follows:

1. A fissured or faulted zone at depth or at a distance from the reservoir and connected to the latter hydraulically.
2. The orientation of the zone at depth is such that the component of shear stress in the direction of the fissures or faults is high.
3. The permeability within the zone is appreciably greater than in the surrounding rock.

In some cases the natural water table may be at a great depth below the reservoir. As a result the increase in pore pressure can be much greater than the depth of the reservoir. This also would tend to increase the delay between impoundment and the development of maximum pore pressure in the rock.

SUMMARY OF CURRENT THEORIES

It appears that the imposition of the dead weight of the impounded water is not in itself sufficient to cause reservoir-associated seismicity. If indeed there is a cause-and-effect relationship (between reservoirs and earthquakes) then the phenomenon may result from a reduction of effective shear strength due to increased pore pressure, acting in conjunction with existing tectonic stresses. The time lag often noticed between attainment of maximum water level and the occurrence of seismic events can be correlated with delays in pore pressure transmissions due to the compressibility of water, as proposed by Lane (17). A secondary cause may be a reduction in shear strength caused by the chemical action of water along discontinuities. For the reservoir to have any significant effects on the seismic regime would require a geologic structure which allows transmission of pore pressures to significant depths or which is susceptible to chemical alteration.

SURVEY OF LARGE U. S. DAMS

If research someday should explain convincingly the mechanism of reservoir-induced seismicity at a particular site, it still would be dangerous to generalize the solution and apply it to another geologic and geographic location. Presently no one explanation has been proved correct for any one site with the exception of fluid injection, and its application to reservoirs is still questionable. To answer the general question regarding the relation of reservoirs to seismic activity it is necessary to free the hypothesis from any one particular failure theory. This might be accomplished by attempting a statistical correlation between the frequency of seismic activity at reservoir sites and the seismic activity of the surrounding region. And to answer the question "How likely are reservoirs to cause seismic activity?", it is necessary to investigate all reservoirs, not just those where seismic activity has been reported.

Information on seismicity of large reservoirs in the United States was obtained by a questionnaire survey of the owners and operators of such reservoirs. The classification of "large" was based on criteria suggested in Ref. 9: dams were classified as large if their hydraulic* height was 100 feet or more; a reservoir was considered large if its capacity was 500,000 acre-ft or more. Seismic events were considered related to the dam if the epicenter was within 10 miles (16 km) of the dam site. Information was sought about any seismic activity occurring within this distance regardless of its magnitude. Two survey forms were used: one was intended for dams which had experienced seismic activity (Figure 1) and the other requested general information on dams where there had been no seismic activity (Figure 2). The structure of the questionnaires points out the major but not necessarily all of the assumptions made in the survey. These are:

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* Maximum water depth adjacent to the dam.

1. "Felt" seismicity (i.e., detectable by man without the aid of instruments) is a realistic measure of the seismic character of a region.
2. Seismic events whose epicenter is within 10 miles (16 km) of a dam site can be attributed to the presence of the reservoir.
3. The frequency of felt seismicity in a region is well-enough defined to permit meaningful comparisons within a region.
4. A dam over 100 feet in height or a reservoir containing over 500,000 acre-ft of water is large enough potentially to induce seismic activity.

RESULTS

The survey provided information on 493 dams. A comparison with the Corps of Engineers Register of Dams in the United States indicated that this sample population was 54% of the total U. S. population of 912 dams that met our criteria. The returns from the dams experiencing seismic activity were often sketchy. Few sites were instrumented and only one, Long Valley Dam (Mono County, California), had any data on seismicity at the site prior to dam construction.* As a result the evaluation of pre-impoundment seismicity was not feasible. Fifty-eight of 493 sites reported seismic activity, but only 20 could report an epicenter for an earthquake with magnitude three or greater within 10 miles (16 km) of the dam site (Figure 3 and Table 3). In almost all cases the epicenters were located from distant recorders; thus the error inherent in the determination of the epicenter may be on the order of miles.

*See "Addenda"

STATISTICAL EVALUATION

The questionnaire results were categorized by seismic risk zones based on the map (Figure 4) presented by Algermissen in 1969 (1)*. As expected most of the dams experiencing seismic activity were located in zone 3, a few in zones 2 and 1, and none in zone 0 (Table 3 and Figures 3 and 4). At this point if it is assumed that reservoirs do not induce seismicity, the question arises "What number of seismic events should be expected to occur within 10 miles (16 km) of the dam sites?" Thus, the probability of occurrence of a seismic event must be examined. To answer this question three dimensions must be defined; (1) what is our definition of a seismic event, i.e., what magnitude of event is of interest?, (2) over what size geographical area is the probability to be estimated, and (3) how long is the period of observation of the area?

The probability is expressed as the number of events of a given magnitude per unit area per unit time. Some calculations of this nature were produced by Algermissen (1). An assumption of this calculation is that the recurrence of earthquakes can be expressed in the form $\log N = a + bI$ where N is the number of earthquakes of intensity I or greater, and a and b are constants. Algermissen developed an expression of this form for the United States. Recognizing the variability of geologic structure in the continental United States, he further developed expressions for nine regions within the United States. These regions are shown in Figure 3.

The questionnaire replies were sorted into Algermissen's nine-region scheme. The regional expressions for probability occurrence

*We became aware of Algermissen's 1976 report (A Probabilistic Estimate of Maximum Acceleration in Rock in the Contiguous United States, USGS Open File Report 76-416) too late for inclusion in this study. However, we believe that the use of the 1976 results would not materially alter our conclusions.

developed by Algermissen are assumed to represent a reasonable model for the regions. However, it is recognized that the expressions are approximate as they were derived from a least-squares line. The minimum magnitude received in the questionnaire replies was 3. To use the Algermissen formulation a conversion, $M = 1 + (2/3)I$, was used, where M is magnitude and I is epicentral intensity. This conversion is crude and in any one application may have considerable error.

The questionnaire data then was compared to the predicted Algermissen values. A comparison could be made only for region 3 (Puget Sound, Washington), region 4 (Rocky Mountains), and region 1 (California). Only in these three regions did the questionnaires indicate an earthquake epicenter within 10 miles (16 km) of a dam. The data for the Rocky Mountain region was used despite the occurrence of only one event with 10 miles (16 km) of a dam. The results of this comparison are given in Table 4.*

CONCLUSIONS

In no case did the seismicity reported in the survey data equal or exceed the predicted seismicity. It has been noted that both the survey data and the predicted values are approximate and the amount of error in the figures is unknown; however, this is the best information available for a statistical evaluation.

We recognize that earthquakes have been reported within the vicinity of some 20**of the "large" dams in the world; but consideration must be given to the fact there are almost 3300 "large" dams**where we have no

**These data are exclusive of the dams in the U. S. and are derived from Ref. 4 and 23.

*More detailed information about the data can be obtained from the authors.

reports of seismic activity. Thus, viewed statistically our study strongly suggests that there is, in general, no appreciable increase in seismicity merely because of the presence of a "large" reservoir. Thus, the probability that a dam with a large reservoir will induce significant seismic activity can be estimated as $P = 20 \div 3300 = 0.007$. The probability of inducing a destructive earthquake is even less. However, no conclusion can be drawn for earthquakes below a "felt" level, that is, below Intensity 3. Finally, we conclude that because of the small number of such occurrences, it would appear that for a potentially destructive earthquake to be initiated near a reservoir a unique combination of circumstances must be present and the probability of such combinations occurring must be very low.

RECOMMENDATIONS

This study is only the first step towards evaluating whether there is a correlation between reservoir proximity and seismicity. The weaknesses in this study direct attention to the need for improving the method of diagnosing the mechanism of reservoir-induced seismicity. This study assumed that any seismic event occurring with 10 miles (16 km) of a dam might have been caused by the reservoir; however, considering the relatively small increase in stress due to reservoir loading, this assumption is conservative. It is possible that a particular event located within this radius may be caused by some phenomenon unrelated to the reservoir loading. Pre-construction seismic instrumentation at the site of large dams could provide a better estimation of the causative effects of the reservoir (4). Especially desirable would be an improved means for estimating focal depth. The installation of several seismographs in the vicinity of the reservoir may remedy the problem of accurate location of the focus. Until the hypocenter can be located with some accuracy and actual measurements made of the stress field at depth, theories regarding the triggering mechanism will remain unproven.

ACKNOWLEDGMENT

We are grateful to all the respondants to our survey for providing the necessary information to conduct this study. In particular we are grateful to Mr. C. F. Corns of the Corps of Engineers for providing their complete inventory of United States dams and to the members of the USCOLD Committee on Earthquakes for their helpful reviews of the draft of this report.

Addendum

Shortly after completing this report, we received a Corps of Engineers study of some 31 operating dams having heights of 200 ft. (60.96m) or more. Their results confirm our conclusions as only Clark Hill Dam (200 ft. high) had experienced a felt earthquake (Magn. 4.3) but this event occurred some 21 years after the first reservoir filling. Only Libby and Dvorshak Dams (both over 100m high and with reservoirs capacities in excess of $4300 \times 10^6 m^3$) were monitored before and after impoundment and these records show microearthquakes that have no apparent relationship to the reservoir operations. They also report that 5 of their completed dams 60.96m high or more are instrumented for microearthquake monitoring; several others are instrumented but still are under construction. (Johnson, S. L., et al, "Reservoirs and Induced Seismicity at Corps of Engineers Projects", Office of Chief of Engineers, Washington, D. C., Miscellaneous Paper S-77-3, January, 1977)

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TABLE 1

REGIONAL b-VALUES (15)

Region	Foreshock b-value (b_F)	Aftershock b-value (b_A)	Regional b-value
Koyna	1.87	1.28	0.47
Kariba	1.13	1.03	0.84
Kremasta	1.41	1.12	0.82

TABLE 2

STATISTICAL SIGNIFICANCE TESTS - DIFFERENCES IN FORESHOCK AND AFTERSHOCK b-VALUES (15)

	Koyna	Kariba	Kremasta
$\frac{b_F}{b_A}$	1.46	1.10	1.26
F-value, 95% Confidence level	1.30	1.09	1.07

Difference in Koyna aftershock b-values and regional values

b-value for Koyna aftershock (b_k) 1.28

b-value for Godavari Valley aftershock (b_G) 0.51

b-value for Peninsular India (b_I) 0.47

$\frac{b_k}{b_G} = 2.51$ $\frac{b_k}{b_I} = 2.72$; F value, 95% confidence interval = 1.27

TABLE 3

DAMS WITH FELT-LEVEL SEISMIC ACTIVITY

Location A (San Francisco area)		
Lafayette	Contra Costa	Joint Event (Note: A joint event occurs when an epicenter falls within the 10-mile radius of more than one dam)
San Pablo	Contra Costa	
Almaden	Santa Clara	Joint Event
Guadalupe	Santa Clara	
Lexington	Santa Clara	
Anderson	Santa Clara	
Coyote	Santa Clara	
Stevens Creek	Santa Clara	
Location B (Santa Barbara County)		
Bradbury		
Location C (Los Angeles area)		
Pacoima		Joint Event
Lower San Fernando		
Location D (Las Vegas area) (Note: arbitrarily included in Region 1)		
Hoover		
Location E (Inyo County)		
Tinemaha		
Haiwee		
Location F (Mono County)		
Long Valley		
Location G (Lake Tahoe area)		
Prosser Creek		Joint Event
Stampede		
Boca		
Location H (King County, Washington)		
Cedar Falls		
Location I (Hungry Horse, Montana)		
Hungry Horse		

TABLE 4

REGION	SURVEY DATA	PREDICTED VALUE
Puget Sound, WA. Region 3	1 event $I \geq 6$ per 1.97×10^7 yr-km^2	16.3 events per 1.0×10^7 yr-km^2
California Region 1	19 events $I \geq 6$ per 15.0×10^7 yr-km^2	84 events per 1.0×10^7 yr-km^2
	6 events $I \geq 7$ per 15.0×10^7 yr-km^2	23.8 events per 1.0×10^7 yr-km^2
Rocky Mountains Region 4	1 event $I \geq 5$ per 1.92×10^7 yr-km^2	64.4 events per 1.0×10^7 yr-km^2

EXPECTED VALUES CONVERTED TO SURVEY OBSERVATION BASE

	No. of Events	Intensity	Predicted No. of Events
Region 3	1	$I \geq 6$	32.1
Region 1	19	$I \geq 6$	1260.3
	6	$I \geq 7$	357.1
Region 4	1	$I \geq 5$	123.9

U. S. COMMITTEE ON LARGE DAMS
COMMITTEE ON EARTHQUAKES

DAMS UNDERGOING SEISMIC EVENTS

1. Name of Dam ____________________

2. River: ____________________ 3. County: __________ 4. State: __________

4a. Latitude & Longitude, if known: Lat: __________ Long: __________

5. Owner:

6. Type of Dam:

Earthfill ( ) Rockfill with ________ face ( ) Gravity ( )
Earth & Rockfill ( ) Concrete Arch ( ) Slab & Buttress ( )
Rockfill w/earth core ( ) Arch Gravity ( )
Other ____________________
(Include maximum cross-section if possible)

7. Dam Height, Foundation to Crest: __________ ft. 8. Maximum Water Depth: __________ ft.

9. Normal Pool Depth at Dam: __________ ft. 10. Maximum Pool Depth at Dam: __________ ft.

11. Reservoir Capacity, Normal Pool: __________ AF 12. Maximum Pool Capacity: __________ AF

13. Dam Construction Started: __________ Completed: __________

14. Reservoir Filling Started On: __________ 14a. Normal Pool Elevation Reached: __________

15. If seismic events have occurred within 10 miles of the reservoir boundaries within historic times, record:

Date	Epicenter Distance (Miles) From Reservoir	Epicenter Distance (Miles) From Dam	Modified Mercalli Intensity Near Dam	Richter Magnitude

(Use additional sheets if necessary for complete event listing)

16. How was seismicity measured?

( ) strong motion recorder on dam ( ) strong motion recorder on abutment
( ) __________ seismographs near reservoir
( ) personal observation of local resident(s)
( ) extrapolation from distant recorders.

17. If seismic recorders are installed, please provide name and address of person who collects and/or maintains the records:

18. Were there any effects on the dam? Yes ( ) No ( )

18a. If yes, please describe same and any required repairs:

19. If seismicity has been observed, please provide as complete a record as possible of reservoir fluctuations from first filling to t present.

20. If there is a geological report that describes the damsite and regional geology, please give title of report and whether it is avai able.

Figure 1. Questionnaire used in the survey (reduced size).

U. S. COMMITTEE ON LARGE DAMS
COMMITTEE ON EARTHQUAKES

DAMS WITHOUT SEISMIC HISTORY

Owner:

Dam Name	State	County/Township	River	Type*	Max. Water Depth (FT.)	Reservoir Capacity (AC.–FT.)

*Dam Type Code: A=Arch; B=Buttress; MA=Multiple Arch; G=Gravity; GA=Gravity Arch; E=Earthfill; R=Rockfill w. Earth Core; RC=Rockfill w. Concrete Face; RA=Rockfill w. Asphalt Face; RS=Rockfill w. Steel Face; ER=Earth–Rockfill; O=Other (describe in footnote)

Figure 2

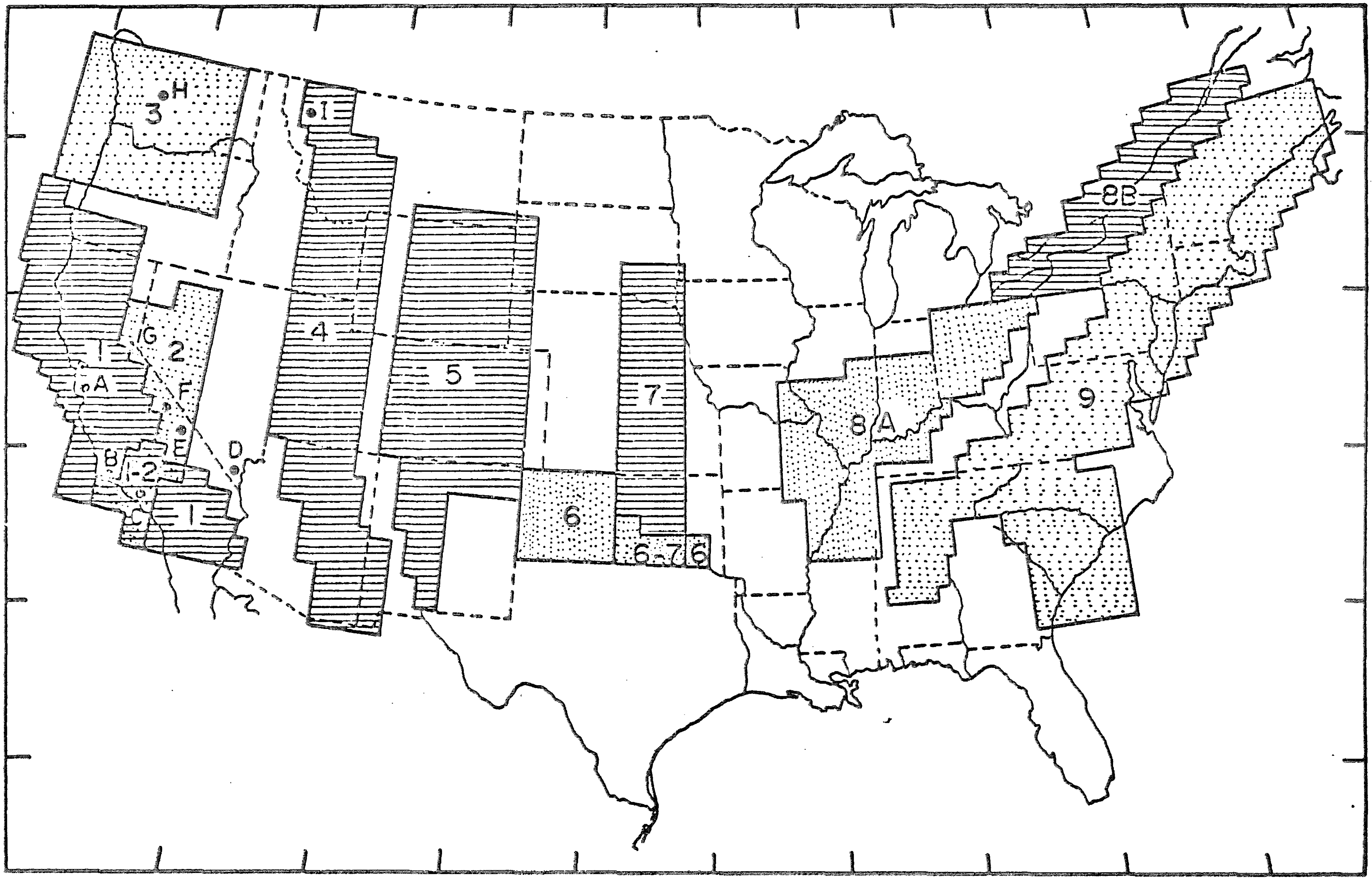

FIGURE 3 LOCATION MAP SHOWING THE AREAS FOR WHICH RECURRENCE FORMULAS WERE COMPUTED (BASE MAP FROM REF. 1)

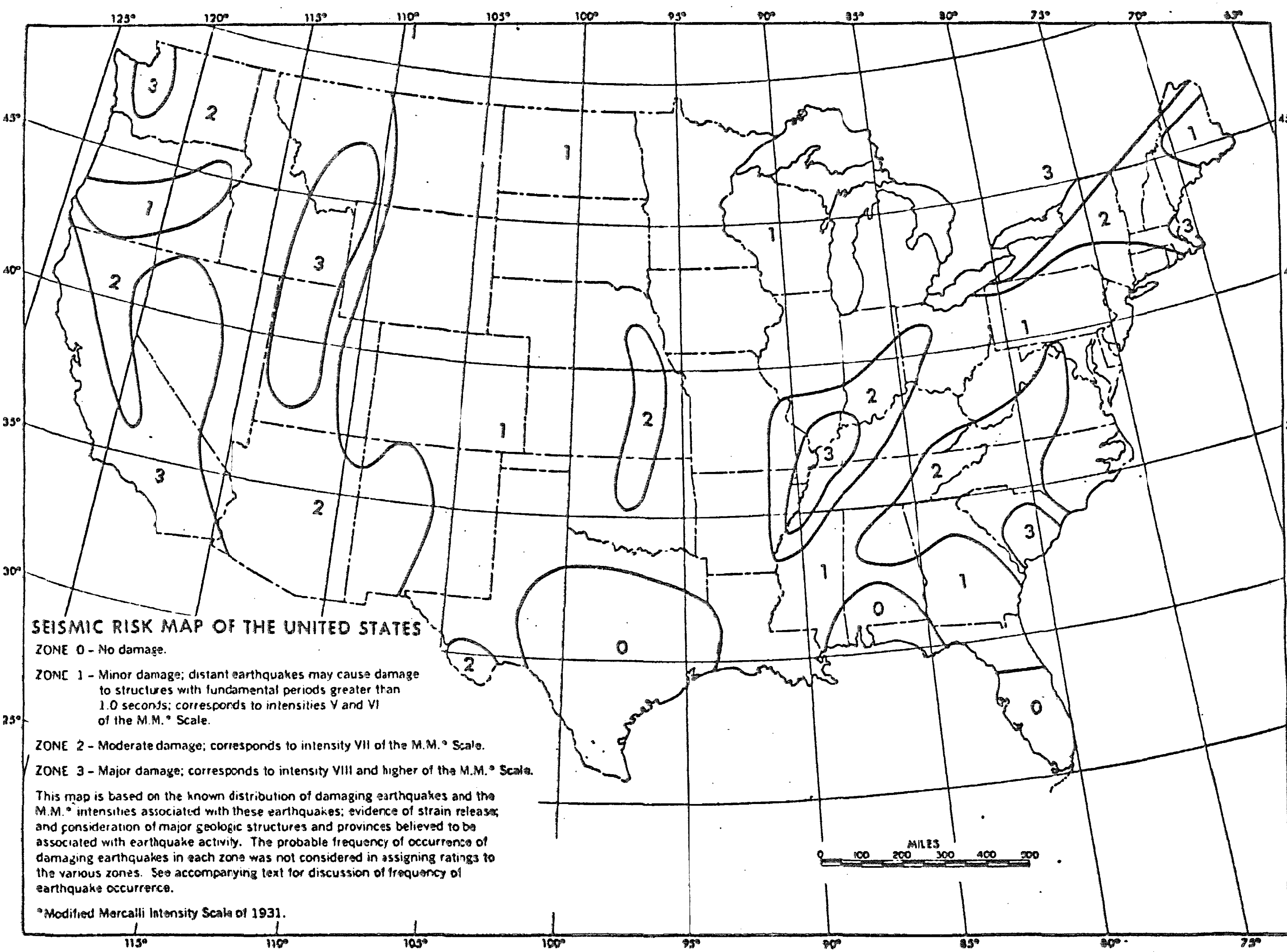

FIGURE 4 SEISMIC RISK MAP OF THE UNITED STATES(1)